

## **THE CLOUDSAT MISSION**

Steven J. Walter\*<sup>1</sup>, Graeme L. Stephens<sup>2</sup>, Deborah G. Vane<sup>1</sup>,

Jet Propulsion Laboratory, California Institute of Technology<sup>1</sup>

Pasadena, CA 91109

Mail Stop 246-101 (Walter)

Telephone: (818) 354-1626 (Walter), Fax: (818) 354-4341 (Walter),

Email: [steven.j.walter@jpl.nasa.gov](mailto:steven.j.walter@jpl.nasa.gov)

Colorado State University, Department of Atmospheric Sciences<sup>2</sup>

Fort Collins, CO 80523

Telephone: (970) 491-8541, Fax: (970) 491-8449

Email: [graeme.stephens@reef.atmos.colostate.edu](mailto:graeme.stephens@reef.atmos.colostate.edu)

### **ABSTRACT**

CloudSat is being proposed to measure the vertical structure of clouds. The spacecraft payload consists of a millimeter-wave radar, an optical imager, and a near-IR spectrometer. CloudSat will fly in formation with ICESat, a NASA EOS laser altimetry mission to acquire concurrent lidar-based profiles of clouds and aerosols. This combination of sensors will allow CloudSat to retrieve profiles and characteristics of multi-layer clouds including measurement of cloud bases and tops with 500-meter accuracy. CloudSat in conjunction with ICESat will determine the profiles of cloud ice and liquid content, optical depth, cloud type, and aerosol properties. The mission's primary goal is to furnish data needed to improve how cloud and cloud-climate feedbacks are parameterized in global circulation models (GCMs). The availability of near-real time cloud and aerosol profiles furnishes an important opportunity to demonstrate active sensor technology for future scientific, civilian, and tactical forecast systems. CloudSat has been proposed to the 1998 NASA Earth System Science Pathfinder (ESSP) Announcement of Opportunity (A.O.). Mission selection is slated for December 1998.

### **MISSION SCIENCE OBJECTIVES**

CloudSat is being developed to investigate how clouds affect climate. Climate is the result of numerous chemical, hydrological, and dynamical processes that work in concert to maintain Earth's energy balance. Clouds are key to defining that balance. Clouds can cool the Earth by reflecting incident sunlight back to space. Clouds can also warm the Earth by either absorbing upwelling thermal radiation and then re-radiating it back toward the surface or sublimating into water vapor, a potent greenhouse gas [Liou, 1996]. The ability of clouds to heat or cool depends on their height, phase (*e.g.*, ice or liquid), distribution of particle sizes, and water content [Brown, *et. al*, 1995]. The CloudSat mission will provide the first global survey of synoptic and seasonal variations of the altitude of clouds and aerosols, including frequency of occurrence. It will also provide quantitative information on cloud-layer thickness, cloud tops and base altitudes, cloud optical thickness, and cloud water and ice content.

CloudSat will fill a gap in existing and planned observational capabilities. Current space systems only use passive sensors. These measurement techniques can only sense the bulk properties of clouds or probe the top-most cloud layer. They are unable to accurately measure the altitudes of cloud bases; retrieve ice and liquid content, or probe the structure of multi-layer clouds. CloudSat will improve validation of numerical weather models by directly measuring cloud characteristics that currently can only be predicted (i.e. vertical profiles of ice and liquid water, and vertical occurrence/overlap).

The CloudSat science objectives are to:

- Quantitatively evaluate the representation of clouds and cloud processes in global atmospheric circulation models, leading to improvements in both weather forecasting and climate prediction;
- Quantitatively evaluate the relationship between the vertical profiles of cloud liquid water and ice content and the radiative heating by clouds.

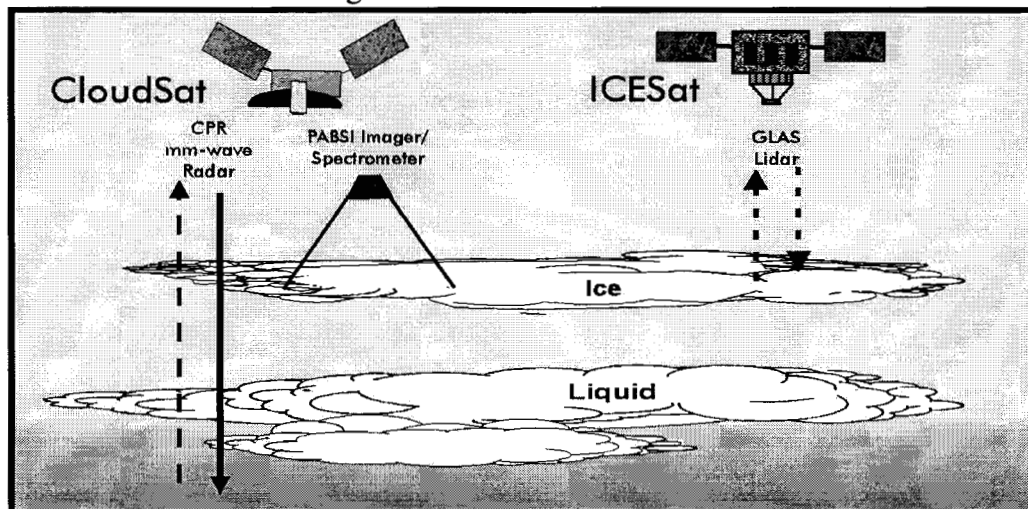
The secondary science objectives are to:

- Improve and validate cloud and aerosol information derived from other research and operational meteorological spacecraft; and
- Improve our understanding of the indirect effect of aerosols on clouds by investigating the effect of aerosols on cloud formation and cloud processes.

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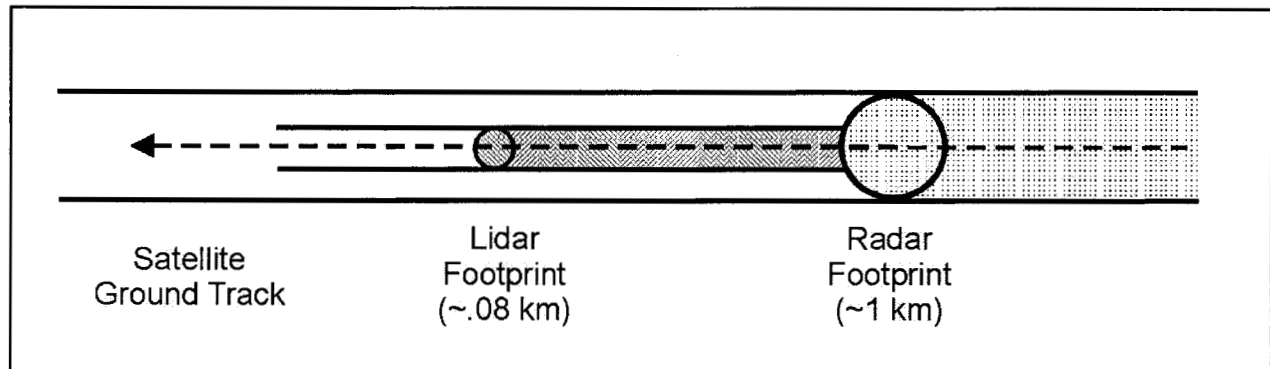
### Mission Overview

The CloudSat payload consists of a 94-GHz Cloud Profiling Radar (CPR) and a near-infrared Profiling A-Band Spectrometer/Visible Imager (PABSI). The CloudSat payload will fly in formation with the EOS ICESat spacecraft, carrying the GLAS lidar. A schematic depicting the mission is shown in Figure 1.



**Figure 1.** CloudSat will achieve a breakthrough in atmospheric sensing by flying in formation with ICESat. Together they will retrieve profiles of cloud ice and liquid content, optical depth, cloud type, and aerosol properties with 500-meter vertical accuracy.

Formation flying enables CloudSat to track the orbit of ICESat. CloudSat will be launched after ICESat and its orbit will be adjusted and monitored to hold the CloudSat spacecraft at a fixed distance from ICESat. The spacecraft will be controlled so that both sets of sensors view the same ground track. In this way, the radar footprint will track the lidar footprint as shown in Figure 2, creating coordinated and essentially simultaneous measurements. The mean separation between the satellites is approximately 450 kilometers which corresponds to a minute delay between lidar and radar measurements. A delay of one minute is a compromise between the desire to minimize the time delay between the radar and lidar measurements and the need to reduce the complexity in the implementation of formation flying.



**Figure 2.** CloudSat will fly in formation with ICESat. The accuracy of the pointing system be sufficient to co-align the foot prints of the radar, lidar, and spectrometer. This strategy will generate nearly concurrent radar and lidar profiles of clouds and aerosols

### Cloud Profiling Radar (CPR)

The CloudSat Cloud Profiling Radar (CPR) provides calibrated radar reflectivity, (e.g., radar backscatter power), as a function of distance from the spacecraft. CPR will be developed jointly by NASA/JPL and the Canadian Space Agency (CSA). The design has a strong heritage derived from existing ground-based and airborne cloud radars [Mead *et. al*, 1994; Sadowy *et. al*, 1997]. The requirements for CPR are dictated by the science objectives. The sensitivity of CPR must provide a minimum detectable reflectivity factor of -30 dBZ and a 70 dB dynamic range. This will allow CPR to detect almost all radiatively significant clouds. The radar footprint is 0.9 km, and will be averaged over 0.3 seconds to produce an effective footprint of 2 km (along-track) by 0.9 km (cross-track). It will yield 500-m vertical resolution and a calibration accuracy of 1.5 dB. The radar footprint necessitates an antenna diameter of 1.85 meters. The antenna pattern requires that the spacecraft be pointed with an accuracy of 0.5° to minimize direct surface reflections and contamination from sidelobes.

The choice of radar frequency, 94 GHz, is a trade-off between sensitivity, antenna gain, atmospheric transmission, and radar transmitter efficiency. Sensitivity and antenna gain increase with frequency while atmospheric transmission and transmitter efficiency decrease with frequency. Since a space-based platform sets strong constraints on antenna size, a frequency of 94 GHz provides an optimum compromise between the competing factors. An international frequency allocation at 94 GHz has recently been set aside for spaceborne radar use. The choice

of frequency means that a small percentage of the time when very thick clouds or heavy precipitation is present, CPR will not be able to penetrate to the cloud base. The mission objective dictates this choice.

A pulse-coding mode has been proposed to boost sensitivity. This technique requires that the radar transmit a long frequency-modulated chirp which is then received and correlated with a replica of the transmitted signal. The longer pulse provides greater power; hence, greater sensitivity. The correlation process reduces the uncertainty in the height of the reflecting layer induced by the longer pulse. However, it increases height resolution at the expense of generating range sidelobes from the surface and highly reflective clouds. The range sidelobes associated with the earth surface will obscure clouds near the ground. Therefore, CPR will have two operational modes. In the normal mode the -30 dBZ sensitivity is achieved using a 3.33  $\mu$ s pulse and 4300 Hz repetition rate. The pulse compression mode will gain -36 dBZ sensitivity with a 33.3  $\mu$ s pulse triggered at an 800 Hz repetition rate.

### **Profiling Oxygen A-Band Spectrometer and Visible Imager (PABSI)**

The Profiling A-Band Spectrometer/Visible Imager (PABSI) instrument both measures the atmospheric radiance of the O<sub>2</sub> A-band rotational spectrum between 761.61 nm and 772.20 nm and records narrow-band images at 747.5 and 761.5 nm. The high-resolution spectrometer determines optical depth and altitude of thin clouds and aerosols by making high spectral resolution (0.5 cm<sup>-1</sup>) measurements at the oxygen A-band. The oxygen A-band is characterized by a “thicket” of closely spaced spectral lines. Therefore, a small change in wavelength will vary the rate at which light is attenuated as it traverses the atmosphere. With measurements made at a wide range of attenuation lengths, it is possible to determine optical depth, photon path length, characteristics of scattering particles, and cloud and aerosol layer altitude [Stephens and Heidinger, 1998]. The imager allows researchers to identify mesoscale weather systems corresponding to the cloud and aerosol profiles. The imager will be able to associate profiles with cloud systems such as tropical storms, cumulus columns, or uniform stratus decks. PABSI has a signal-to-noise of 1000:1 that will enable measurement of cloud and aerosols with an optical depth of 0.02 to 3% accuracy. Both the imager and spectrometer measure reflected sunlight and thus can only operate during daylight.

The imager and the spectrometer are integrated into the same instrument and share most of the same optics. The PABSI detectors are 1024 by 1024 element CCDs with 11 micron square pixels. These devices can be operated without active cooling and are photon-noise limited in this application. Although the imager and spectrometer have different field-of-views (FOVs) and resolution requirements, both systems can use the same CCD detectors. The required spatial and spectral resolution is obtained by summing the pixels. The imager readout electronics uses a 12-bit A/D converter, while the spectrometer's uses a 14-bit A/D converter. This allows the spectrometer to better resolve the radiances observed in the cores of strong O<sub>2</sub> lines where attenuation is high. The imager and spectrometer employ microcontroller-managed FPGA-based digital signal processors that can be reprogrammed on-orbit providing operation flexibility. The processors will be able to

compensate for small changes in instrument alignment that could occur during testing, integration, or on-orbit.

The instrument gathers data synchronously. It operates in a push broom mode utilizing a rectangular instantaneous field-of-view (FOV). A cloud or aerosol feature is first imaged by the 747.5 nm imaging channel with a 15 km swath and an instantaneous field-of-view (IFOV) of 0.5 km. PABSI then makes a measurement with the A-Band spectrometer using a single 0.9-km square footprint (matched to the CPR). Finally, the 761.5 nm imager which also has a 15 km swath and 0.5 km IFOV records an image. This cycle is then repeated.

## **GLAS Lidar**

The primary mission for the ICESat Geoscience Laser Altimeter System (GLAS) is to monitor the amount of ice in the polar ice sheets and investigate how the ice sheets affect changes in global sea level. The secondary missions for GLAS is to measure clouds and aerosols, map surface topography, and measure characteristics of the Earth surface especially vegetation, snow-cover, and sea-ice. To achieve the secondary atmospheric objective, GLAS will measure the vertical structure of radiatively significant clouds and aerosols up to the signal attenuation limit at approximately 2 optical depths [Rogers, 1976]. The lidar will measure range-resolved profiles of lidar backscatter with a vertical resolution of 70 m. At this resolution, lidar sensitivity for a 100 m instantaneous field of view is expected to be  $10^{-5} \text{ m.sr}^{-1}$  corresponding to a cloud or aerosol optical depth of  $\sim 0.05$ . GLAS sensitivity to very thin clouds and aerosols combined with its enhanced vertical resolution complements the CloudSat measurements.

The GLAS lidar uses a solid state, diode pumped Nd:YAG (neodymium-yttrium-garnet) laser that transmits 4 nanosecond pulses of infrared light (120 mJ @ 1.064 nm) and green light (60 mJ @ 532 nm) using a repetition rate of 40 Hz. GLAS has an 80-cm diameter telescope that yields a 70 meter footprint that is sampled at 170-meter intervals. The GLAS footprint can be located to within a few meters using a GPS and star tracker-guided positioning and attitude control systems. The required design lifetime for ICESat is 3 years with a 5-year lifetime goal.

## **Spacecraft**

The CloudSat mission was designed with a two-year lifetime to enable more than one seasonal cycle to be observed. The desired orbit is the ICESat orbit which is a nearly sun-synchronous, 600 km altitude orbit that is inclined at  $94^\circ$ . This orbit will provide hundreds and in some cases thousands of observations that are coincident with the EOS platforms, the Defense Meteorological Satellites, the NOAA Geostationary Weather Satellites (GOES), and international satellites. These concurrent observations will allow validation of the passive meteorological sensor retrieval algorithms with the CloudSat/ICESat active sensor measurements. This will create a unique data base with which to improve the passive sensor retrievals that are dependent on assumptions about cloud height and cloud properties.

CloudSat is designed around the Ball Aerospace RS2000 spacecraft bus that is being used for both QuikScat and ICESat. Communications is accomplished via an S-band transceiver using a nearly, omni-directional patch antenna. The maximum mass of the commercial spacecraft will not exceed 700 kg and the spacecraft subsystems and payload will require a maximum power level of 1170 W.

CloudSat is a proposed NASA mission; however it draws on support and expertise from DoD, DOE, NOAA, universities, federal laboratories, industry, foreign agencies and institutes. Notably, the U. S. Air Force Space Test Program will provide ground operations and manage communications. The Cooperative Institute for Research in the Atmosphere (CIRA) at the Colorado State University (CSU) will handle data processing and archiving the data. The Jet Propulsion Lab will be responsible for mission operations and payload development. Ball Aerospace is providing the spacecraft bus and will be responsible for spacecraft integration and test. Independent calibration of the instrument payload will take advantage of ground-based observational sites such as the DOE Cloud and Radiation Test bed (CART) sites, NASA airborne science campaigns, and university and government research facilities including the University of Utah, Penn State, GKSS in Germany, the NOAA Environmental Technology Lab, Atmospheric Environmental Services (AES) in Canada, and the Communication Research Lab (CRL) in Japan.

## CONCLUSIONS

CloudSat is being developed to measure the vertical structure of clouds and aerosols from space. It combines a cloud profiling radar with a profiling A-band spectrometer that is integrated with a visible imager. The ICESat GLAS lidar will complement the CloudSat CPR and PABSI data. CloudSat in conjunction with ICESat will determine the profiles of cloud ice and liquid content, optical depth, cloud type, and aerosol properties. This payload is designed to profile clouds with 500 meter resolution, detect very thin clouds, image the regional cloud field and assist in validating measurements made by the NASA Earth Observing System (EOS) and other meteorological satellites such as the Defense Meteorological Satellites (DMSP). CloudSat is cooperative effort that includes international partners, universities, and U. S. government agencies. CloudSat will furnish an important technology demonstration for future scientific, civilian, and tactical forecast systems. CloudSat has been proposed in response to the 1998 NASA Earth System Science Pathfinder (ESSP) Announcement of Opportunity (A.O.). ESSP mission selections are expected to be announced during December 1998.

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